Numerical simulation of roadway gas migration based on the lattice Bolzmann method

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Abstract

Coal roadway tunneling could result in redistribution of stresses in the coal body around the roadway, and cause the spatially uneven distribution of permeability in the coal body around roadway both in the radial direction and the axial direction. Considering this engineering fact and using the lattice Boltzmann method, the migration law of the gas is studied in the coal body around the roadway. Research shows that: as time goes on, the gas pressure dropped area of the coal body will gradually increases; along the radical direction of the roadway, the gas pressure gradient in the coal body closer to the roadway wall would gradually decrease, whereas the gas pressure gradient in the coal body farther from the roadway wall would gradually increase, and at the locations with stress concentration and low permeability, because the gas flow is easily blocked, it would be likely to cause a higher gas pressure gradient; the model for calculating the gas emission quantity of the roadway is given, and the calculated results can provide the basis for the ventilation design of the roadway.

Key words: roadway; gas migration; permeability; the lattice Boltzmann; pressure distribution; gas emission quantity

1. Introduction

40% of the coal mine gas accidents are in the process of coal roadway driving. With the mine deepening gradually, the pressure of the gas and the amount of the gas emission in the working face increased remarkably, and the problem of return air and transfinite gas in the upper corner is on the rise. It is of great significance to master the distribution of gas pressure and gas emission law in the tunneling face, accurately predicting the amount of gas emission for effectively governing the gas disaster.

Tunneling working face gas flow rule is a prerequisite for the control of heading face gas accident. Scholars like Zhou Shining etc. studied the coupling of gas migration and deformation of the coal from different angles, and they made a numerical modeling to the flow of the coal seam gas. In these studies, Seepage model almost take the coal and rock mass and gas as a continuous, homogeneous medium, obtaining the partial differential equations by classical mechanics method, transfer partial differential equations into algebraic equation through Taylor expansion to get the solution, so you can call it a top-down approach.

In contrast, the lattice Boltzmann method (LBM) establish micro model and models that meet conservation law to evolve the rule, which is in order to get a result that satisfy the macro transport law, so it is a bottom-up way of simulation.

On the basis of the description to the microscopic movement of physical systems, LBM established a model that directly simulated the evolution of physical systems, macroscopic physical quantities are calculated by the evolution equations of the model, thus establishing the linkages between the macroscopic physical quantity and the microstructure evolution. Because of the micro background, LBM is more convenient in dealing with complicated boundary.

In this paper, we used LBM method to study the gas migration in the coal around the tunneling roadway. Considering the tunneling engineering will make the coal stress redistribution, resulting in penetration of both sides of the wall of coal roadway tunnel along the radial, and the front of the coal wall of coal body along the strike are not uniform. In the course of the study coal permeability is considered as piecewise functions along the changes of crustal stress. The results can provide the basis for the tunneling working surface gas outburst prevention.

2. The LBE of fluid flow in porous media

For Isothermal flow of incompressible fluid in porous media, Nithiarasu proposed a general percolation model, which contains not only linear resistance (Darcy) and viscosity (Brinkman), but also non-linear resistance term (Forchheimer). The model can be expressed in the form of generalized Navier-Stokes equations:

$$\nabla \cdot \boldsymbol{u} = 0$$

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)(\frac{\boldsymbol{u}}{\varepsilon}) = -\frac{1}{\rho}\nabla(\varepsilon p) + \upsilon_e \nabla^2 \boldsymbol{u} + \boldsymbol{F} \quad (1)$$

Where ρ is the fluid density, u and p is the apparent velocity and pressure, $\upsilon_e = \mu_e / \rho$ is the effective coefficient of kinematic viscosity, F is the total force including the external force and the resistance of medium:

$$\boldsymbol{F} = -\frac{\varepsilon\upsilon}{K}\boldsymbol{u} - \frac{\varepsilon F_\varepsilon}{\sqrt{K}}|\boldsymbol{u}|\boldsymbol{u} + \varepsilon G \qquad (2)$$

Where ν is the viscosity of the fluid, G is the external body force and K is the permeability. The structure function Fε is given by Ergun equation [8]:

$$F_\varepsilon = \frac{\mathbf{1.75}}{\sqrt{\mathbf{150}\varepsilon^3}} \qquad (3)$$

GUO Zhao Li constructed a LBE model that can be used to solve the generalized Navier-Stokes equations, and the evolution equation [7] is:

$$f_i(\boldsymbol{x}+\boldsymbol{c}_i\delta_t, t+\delta_t) - f_i(\boldsymbol{x},t) = -\frac{1}{\tau}(f_i(\boldsymbol{x},t) - f_i^{(eq)}(\boldsymbol{x},t)) + \delta_t \boldsymbol{F}_i \qquad (4)$$

Among which：

$$f_i^{(eq)} = \omega_i \rho\left[1 + \frac{\boldsymbol{c}_i\cdot\boldsymbol{u}}{c_s^2} + \frac{\boldsymbol{uu}:(\boldsymbol{c}_i\cdot\boldsymbol{c}_i - c_s^2\boldsymbol{I})}{2\varepsilon c_s^4}\right] (5)$$

$$F_i = \omega_i \rho(1-\frac{1}{2\tau})\left[\frac{\boldsymbol{c}_i\cdot\boldsymbol{F}}{c_s^2} + \frac{\boldsymbol{uF}:(\boldsymbol{c}_i\boldsymbol{c}_i - c_s^2\boldsymbol{I})}{\varepsilon c_s^4}\right] (6)$$

$\boldsymbol{F}$ in the formula of (6) is given by the formula of (2). Flow density and velocity is defined as:

$$\rho = \sum_i f_i \text{ , } \rho\boldsymbol{u} = \sum_i \boldsymbol{c}_i f_i + \frac{\delta_t}{2}\rho\boldsymbol{F} \qquad (7)$$

Since $\boldsymbol{F}$ contains flow velocity $\boldsymbol{u}$, so the equation (7) is quadratic non-linear equations for velocity $\boldsymbol{u}$

$$\boldsymbol{u} = \frac{\boldsymbol{v}}{c_0 + \sqrt{c_0^2 + c_1|\boldsymbol{v}|}}$$

Where V is a temporary speed, namely:

$$\rho\boldsymbol{v} = \sum_i \boldsymbol{c}_i f_i + \frac{\delta_t}{2}\varepsilon\rho\boldsymbol{G} \qquad (8)$$

Where the parameters c_0 and c_1 are:

$$c_0 = \frac{1}{2}(1+\varepsilon\frac{\delta_t}{2}\frac{\upsilon}{K}) \text{ , } c_1 = \varepsilon\frac{\delta_t}{2}\frac{F_\varepsilon}{\sqrt{K}} \qquad (9)$$

To analysis the macro performance of the microscopic model, a multi-scale theory is needed. The corresponding macroscopic equations can be obtained by analyzing the LBE (4) in Chapman-Enskog, which are generalized Navier-Stokes equations (1).

3. The LBM model of gas flow field in heading face and the example simulation

By using the LBM method, gas flow is simulated on the roadway. The roadway and its surrounding coal horizontal profile map is shown in figure 1. The part of Fill Pattern in figure 1 is coal seam and Region 5 is roadway. In Region 3 and Region 4, coal body can be regarded as unaffected by tunneling, and its permeability is still original coal permeability. Coal body in Region 1, region 2 and region 6 are all influenced by the roadway, resulting in the redistribution of stress, and the permeability changes. The original permeability of coal body is $K_0=5\times10^{-12}\text{m}^2$ and original porosity is $\varepsilon=0.1$, and assumption that the stress redistribution have a little impact on the porosity of coal body, and it remains the original porosity and changes a little.

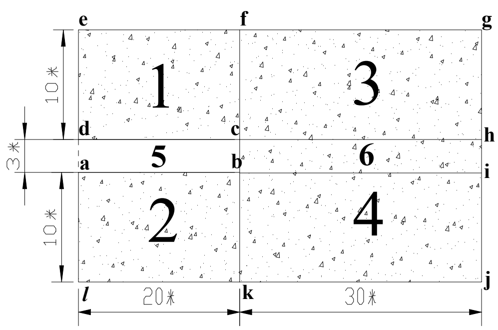


Fig.1 The horizontal profile map of the roadway and its surrounding coal body

After stress redistribution, coal permeability in region 1 presents uneven distribution along the direction of de, its permeability K comply with the following section function (Fig. 2) :

$$K=\begin{cases}8\times K_0 e^{-1.4607y} & (0\le y<3m)\\ K_0\times(0.3y-0.8) & (3\le y<6m)\\ K_0 & (6\le y\le 10m)\end{cases} \quad (11)$$

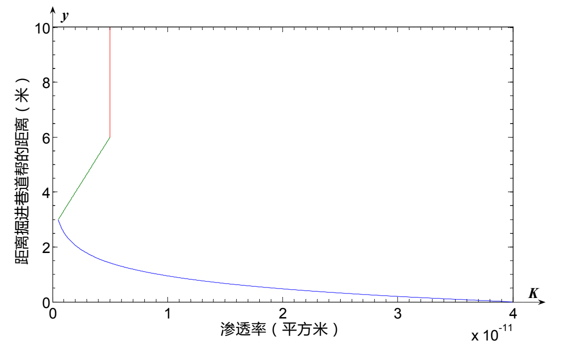


Fig.2 The permeability distribution of coal body along the radial direction of the roadway

The original point in figure 2 is point d in figure 1, and the coordinate of y axis is shown as de direction in figure, y in formula (11) represents the area of the distance away from the lane to help (i.e. the line dc). And suppose that the coal permeability in region 2 and region 1 are symmetrical on the roadway (abcd).

In region 6 (ahead of tunneling) coal permeability in ch direction is not uniform distribution, and permeability satisfies the following subsection function (Fig..3):

$$K=\begin{cases}7\times K_0 e^{-0.3555x} & (0\le x<10m)\\ K_0\times(0.08x-0.6) & (10\le x<20m)\\ K_0 & (20\le x\le 30m)\end{cases} \quad (12)$$

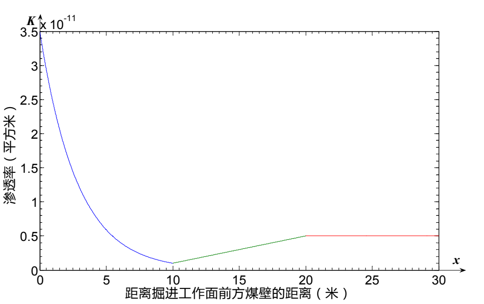


Fig.3 The permeability distribution of coal

body along the axial direction of the roadway

The original point of figure 3 is point b in figure 1, and x axis is in the same direction of ch in figure 1. Among formula (12), x represented the distance to tunneling working face of coal wall in region 6 (i.e., line bc).

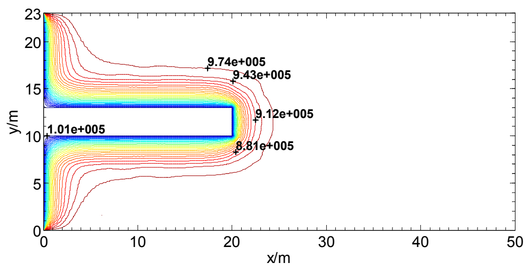
D2Q9 model is adopted to do numerical simulation for the example, studying the gas migration law around the roadway of coal, and ignore the impact of its own gravity during the simulation of coal seam gas migration process, at the same time the whole process is an isothermal process, the temperature is 25 ℃. We arranged 5 grids per 1 m length of coal, so as to all borders, lattice distance dx = 0.2 m. The initial state of coal body gas pressure is 1.0MPa, on the boundary e-d-c-b-a-*l* lattice, the initial pressure is 0.101Mpa, on the boundary e-f-g-h-i-j-k-*l*, initial pressure point is 1.0MPa, and the pressure on the boundary grid points remains constant, and we used the non-equilibrium extrapolation scheme [9] to deal with the stress boundary condition. When taking the gas dynamic viscosity as 0.5505MPa at 25 ℃ (average of inlet and outlet pressure) the dynamic viscosity of methane, namely $\mu = 1.112749 \times 10^{-5}$ Pa·s. According to $\upsilon_e = c_s^2(\tau - 0.5)\delta_t$ and D2Q9 model $c_s^2 = \frac{c^2}{3}$, $c = dx/\delta_t$ to give $\delta_t = \frac{(\tau - 0.5)\times(dx)^2}{3\upsilon_e}$, take $c = dx/\delta_t$, when taking the effective kinematic viscosity υ_e as mean pressure (i.e., the average inlet and outlet pressure), the kinematic viscosity of methane $\upsilon_e = 3.093771 \times 10^{-6}$ m2/s.

The program flow is as follows: (1) initialize distribution function in each lattice point ; (2) at time t, perform collision steps for each grid point (including border grid) to determine the speed distribution function of each grid point after the moment; (3) perform the migration for all internal grid points (excluding the boundary grid point), and get distribution function the next moments before the collision for each grid point on the inside; (4) calculate the amount of macro; (5) repeat steps (2) to (4), until the error meets the requirements.

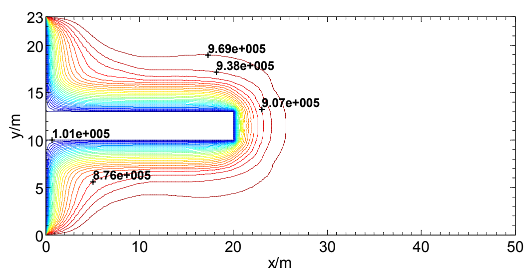
4. Simulation results and analysis

4.1 The distribution of gas pressure around the coal roadway

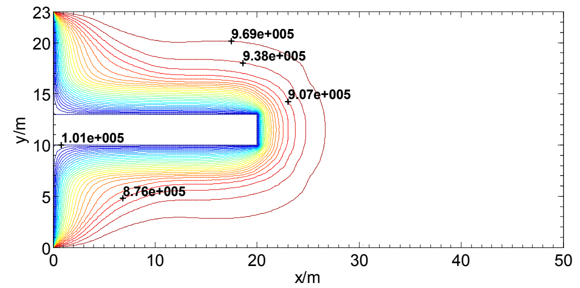
With the driving of roadway and the gush of coal seam gas through the exposed wall surface constantly, the pressure of coal seam gas change constantly. Figure 4 shows the contour map of gas pressure in different moment.



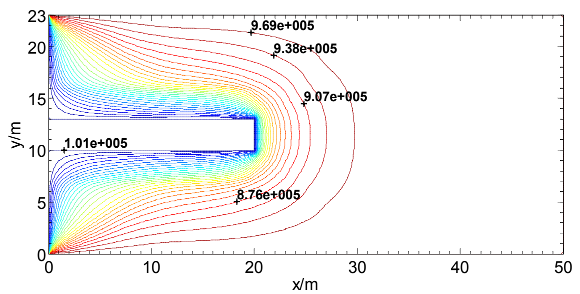
(a) After 0.6266 days the gas pressure contour map of coal body.



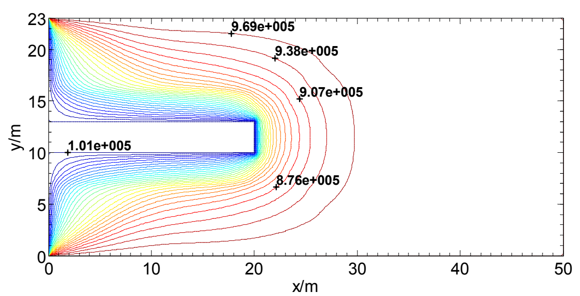
(b) After 1.2532 days the gas pressure contour map of coal body.



(c) After 1.8798 days the gas pressure contour map of coal body.



(d) After 37.5972 days the gas pressure contour map of coal body.



(e) After 75.1944 days the gas pressure contour map of coal body

Fig.4 The gas pressure contour map of coal body around the roadway at different moments

The distribution of gas pressure can be seen clearly around the coal from figure 4. As time goes on, affected by the gas emission of roadway, the scope that have lower gas pressure increased constantly, until gas flow field reaches a steady state, and the distribution of stress won't change.

4.2 Gradient distribution of gas pressure in coal body

Choose the lattice point of perpendicular bisector in dc line from region 1 in figure 1. And study the relationship between gas pressure and its distance to the tunnel wall in lattice points, we can obtain the pressure distribution curves as shown in figure 5, and map the corresponding pressure gradient diagram, as shown in figure 6. In figure 5 the pressure distribution curve has overlapped in 37.5972 days and 75.1944 days, which illustrates the gas flow field has reached steady state after 37 days and the flow field of gas pressure distribution won't change since then.

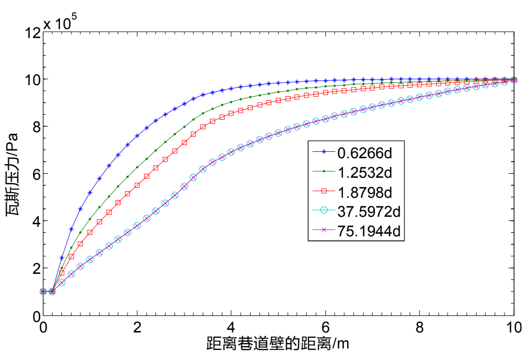


Fig.5 The relationship between gas pressure in the coal body and the distance away from the roadway wall

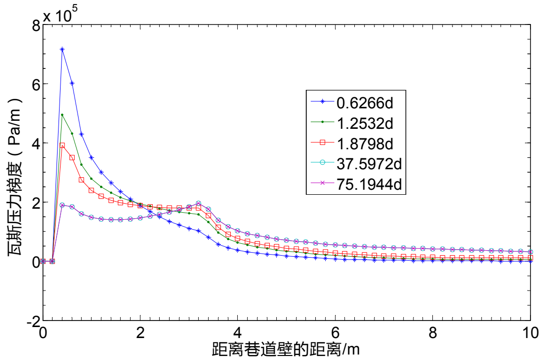


Fig.6 The relationship between gas pressure gradient in the coal body and the distance away from the roadway wall

In figure 6, at the beginning of roadway gas leaking (after 0.6266 days) the gas pressure gradient near the wall is large. The gas pressure gradient far away from the roadway wall is almost 0. As time goes on, the gas pressure gradient decreases around the coal wall, while gas pressure gradient far away from the tunnel wall increases.

There are two peaks in the pressure gradient, which can be seen from two curves of gas pressure gradient from 37.5972nd day and 75.1944th day. One is about 0.4 meters from the tunnel wall; the other is about 3 meters away from the roadway wall, where is the position both stress concentration and low permeability in region 1, places like that will easily result in the block of gas migration, and have a higher pressure gradient.

In figure 1 by selecting the lattice point of perpendicular bisector from line bc from region 6, and researching the relationships between gas pressure at the lattice point and their distance to the head tunneling of the coal wall, the pressure distribution curves are obtained as shown in Figure 7 and the corresponding pressure gradient map is drawn as Figure 8.

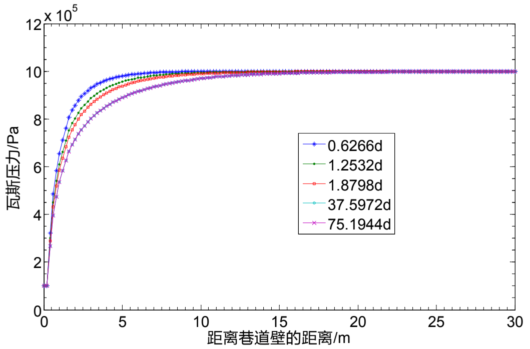


Fig.7 The gas pressure distribution of the coal body ahead of the tunneling working face

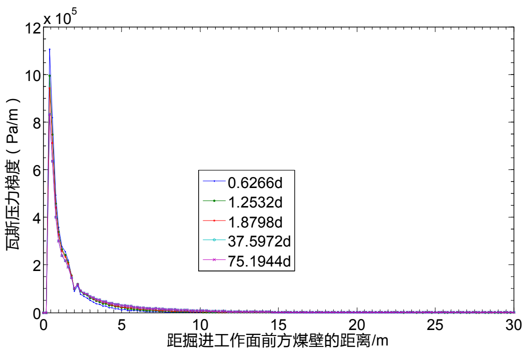


Fig.8 The relationship between gas pressure gradient of the coal body ahead of the tunneling working face and the distance away from the tunneling working face

Figure 7 shows that after digging 0.6 days, the gas pressure has basically reached the initial gas pressure five meters away from heading end. With the increase of exposure time of the coal wall (stable after 37 days), gas pressure reaches the initial gas pressure at the 10-15 meters away from the heading end. Figure 8 shows that the peak of gas pressure gradient (40% than gas pressure gradient peak in figure 6) appears at 1 meter away from the head.

Within 2.5 meters away from tunneling head, the gas pressure gradient is big. As the coal and gas outburst is under the effect of high gas pressure gradient, the gas pressure torn and thrown out of the coal, Therefore, stress concentration zone in the front tunneling head is a dangerous area of coal and gas outburst.

5. Conclusions

(1) We have simulated the roadway gas migration by using the lattice Boltzmann method. As the tunneling work will make coal stress redistribution, leading to the coal permeability not evenly distributed. In the simulation process, considering the permeability along the radial roadway and the front of coalface changes with the stress, and the permeability is expressed by piecewise functions.

(2) Gas pressure distribution diagram around the coal roadway in different time shows that the area of lower gas pressure

increased as the time goes on, which is affected by the gas emission of roadway, but eventually gas flow field reach the steady state, and the pressure distribution won't change.

(3) As the time goes on gas pressure distribution curve and the corresponding gas pressure gradient distribution curve shows that the gas pressure gradient near the roadway coal wall decreases, while gas pressure gradient far from the tunnel coal wall increases. Stress concentration area, where low permeability gas flow will easily lead to blockage, it will result in higher pressure gradient in this area, becoming coal and gas outburst danger zone.

(4) We can get the gas velocity vector and flow field flow diagram at different time. The flow rate on the exposed coal body was significantly quicker than the internal gas flow rate, as time goes on, the gas velocity on the exposed surface decreases gradually. The gas continued gushing from the exposed surface of roadway and reproduction the gas flow process from the coal to roadway.

(5) Having given a method for calculating the amount of roadway gas emission, we can calculate the amount of gushed gas at any time, providing the basis for tunnel ventilation operation calculation.

6. References

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